

MODELING PERFORMANCE OF AN AIRBORNE INFRARED SENSOR USED BY A MAN-IN-THE-LOOP IN TACTICAL AIRCRAFT DURING DAYLIGHT OPERATIONS

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ABSTRACT

The performance of a man-in-the-loop using an IR sensor in a tactical aircraft, in daylight, is severely limited by the cockpit display. Any FLIR performance prediction model that fails to take the display effects into account will yield very optimistic results. The best monochromatic tactical aircraft displays are contrast limited during daylight operations and are able to reproduce only a fraction of the available dynamic range of current generation IR imaging sensors. Polychromatic cockpit displays used to view imagery limit daylight performance even further.

BACKGROUND

The Army FLIR92 Thermal Imaging Systems Performance Model is used by many analysts to predict the performance of a MITL using an IR sensor. The model is recognized as an industry standard and has proved itself to be very useful in making reasonable performance predictions for a variety of applications. The predicted performance of night vision equipment and eye shielded daylight equipment, using FLIR92, has been confirmed repeatedly during field testing.

Unfortunately, the model becomes less accurate and overly optimistic when it is used to predict what Biberman described as the worst hardware situation: "equipment designs as are proposed for high performance aircraft". The model makes major assumptions in key areas, that are weak when applied to tactical aircraft operations in daylight. The model calculates a 2D MRTD function for an IR system, based on a set of sensor, display and eye parameters supplied by the user (or as default values). The calculated 2D MRTD is then made the basis for subsequent performance predictions based on Johnson's criteria, etc. When inputting terms into the model it is important to use appropriate eye integration times, threshold signal-to-noise ratios and other key parameter values (rather than the default values) to account for the tactical aircraft environment and mission success criteria. The User's Guide cautions the analyst that many of the default parameter values are based on optimum viewing conditions.

The model was written to predict performance during night operations and contrast reducing effects due to glare on the display are not modeled directly. It is possible to discretely input a modified display modulation transfer function that contains an additional term in the denominator to account for glare. Unfortunately, contrast changes are not represented in the 2D MRTD equations (except as an MTF modifier). The model will define performance based on the calculated 2D MRTD regardless of the

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| 14. ABSTRACT The performance of a man-in-the-loop using an IR sensor in a tactical aircraft, in daylight, is severely limited by the cockpit display. Any FLIR performance prediction model that fails to take the display effects into account will yield very optimistic results. The best monochromatic tactical aircraft displays are contrast limited during daylight operations and are able to reproduce only a fraction of the available dynamic range of current generation IR imaging sensors. Polychromatic cockpit displays used to view imagery limit daylight performance even further. | | | | | |
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available contrast. Contrast will be the limiting performance factor (rather than 2D MRTD) under most daylight viewing conditions, to the extent that that the 2D MRTD metric becomes inconsequential.

EXAMPLES OF THE GLARE EFFECT ON DISPLAYED VIDEO

The following four figures illustrate how displayed imagery is affected by glare. The examples are qualitative in nature. Figures 1 and 2 are identically processed photographs of a standard gray scale target, recorded on video and displayed on a commercial monitor, with and without glare present on the screen. The video system used had limited dynamic range but was able to reproduce about 15 discernible contrast steps when there was no glare present. In the presence of glare the ability to distinguish between adjacent steps was severely impacted. Figures 3 and 4 are identically processed photographs of high contrast FLIR video, displayed on a monitor, with and without glare present on the screen. The system is FLIR limited in figure 3 and display limited in figure 4.

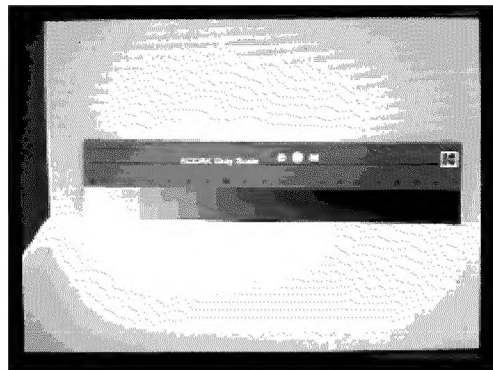


Figure 1. Displayed image of photographic gray shade card when no glare is present on display

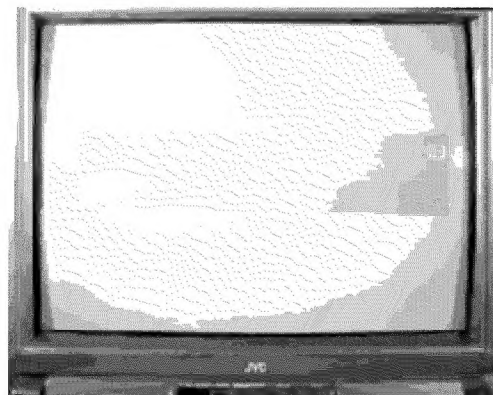


Figure 2. Displayed image of photographic gray shade card when glare is present on display



Figure 3. Displayed FLIR imagery when no glare is present on the display



Figure 4. Displayed FLIR imagery when glare is present on the display

EYE INTEGRATION TIME

The FLIR92 model uses a default and recommended eye integration time (t_E) of 0.1 seconds. The default value is reasonable if the sensor is going to be used at night or when an eye shroud is available. The default is not the correct number to use in the model if neither of the previously named conditions apply.

The eye integration time (t_E) is a function of the ambient lighting conditions. Rose and others initially theorized that the eye obeyed a reciprocity law, where by the storage time of the eye was inversely proportional to the scene brightness, and ranged between 0.1 and 0.2 seconds. Shade and others subsequently confirmed Rose's reciprocity law. However, they modified the model for daylight viewing conditions (10K ft-L) as shown in figure 5.

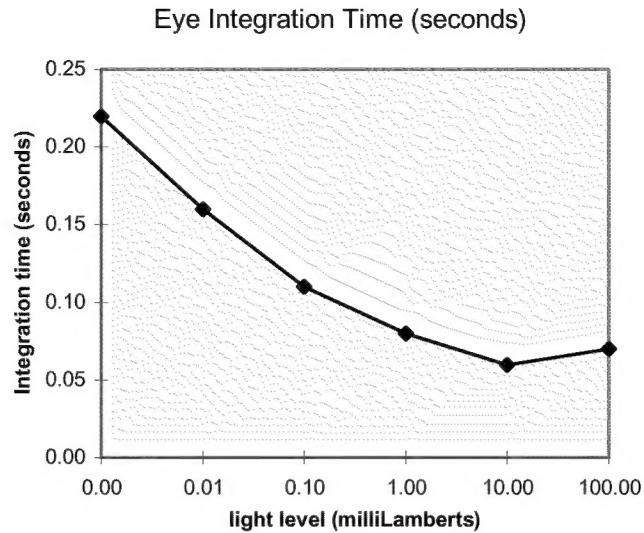


Figure 5. Eye integration time as a function of scene brightness

This is significant in tactical aircraft sensors intended to be used during daylight operations. The horizontal, vertical and 2 dimensional (2D) MRT functions, in the FLIR92 Analyst's Reference Guide, can be written in the form:

$$\text{MRT} = \frac{\text{SNR}_{\text{TH}}}{(t_E)^{0.5}} * [\text{everything else}]$$

The accepted standard for maximum daylight ambient lighting conditions, which the F-16 and F-18 displays are designed to operate in, is 10K ft-L. Figure 5 shows that t_E approaches a minimum well below the maximum expected brightness level. Any daylight model should reflect this and have a value of .06 or .07. Figure 6 illustrates how the MRT of a sensor increases as t_E is decreased (due to daylight viewing conditions).

CONTRAST LIMITED PERFORMANCE

High performance aircraft displays use a combination of narrow band phosphors, anti-reflection coatings on the CRT faces and notched spectral bandpass filters, to maximize contrast during daylight operation. The best monochromatic displays using rare earth phosphors (such as P-43) reduce the combined specular and diffuse glare contributions from incident sunlight, to about 50 ft-L in 10K ft-L operating conditions. Polychromatic displays that provide multiple colors have wider optical bandwidths, and correspondingly less efficient filters and coatings. The best polychromatic displays only reduce the combined specular and diffuse glare contributions to about 93 ft-L in 10K ft-L operating conditions. The large veiling glare term makes an aircraft display used to display FLIR video during daylight contrast limited. This is shown in the following figures. Scott first defined the Demand Modulation function to predict the contrast required to support just-resolvable imagery on displays. It is more commonly known today as the Threshold Modulation (TM) function. TM curves assume optimum viewing distance and adequate (perhaps limited) viewing time, neither of which are usually achievable for air-to-ground search.

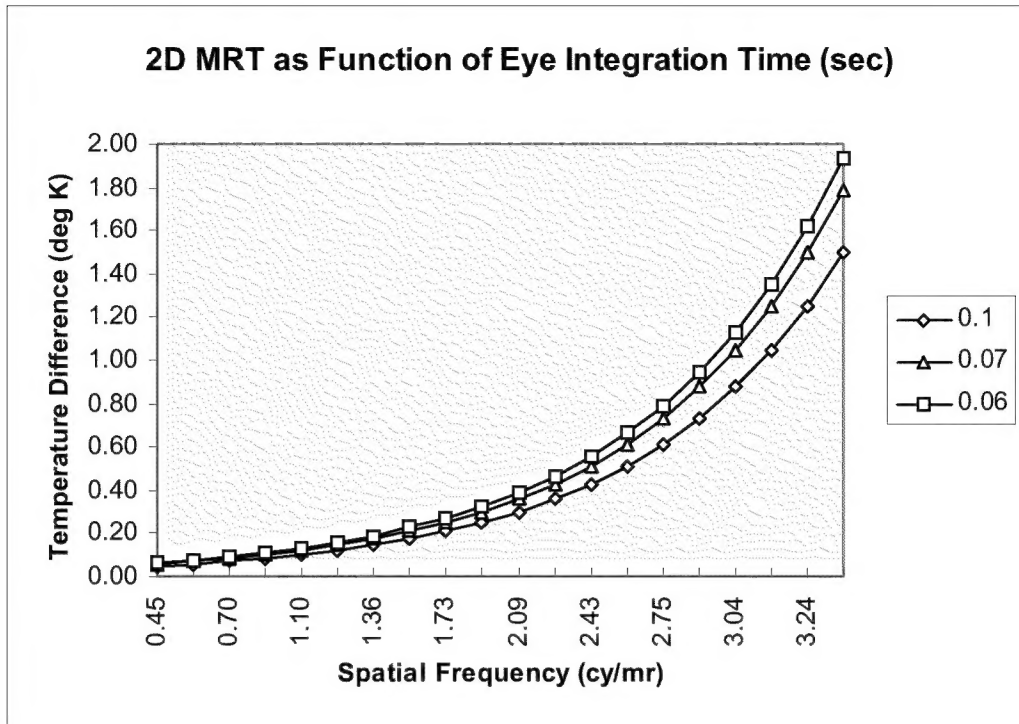


Figure 6. MRT as a function of eye integration times (for $t_E = 0.06, .07$ and 0.10 sec)

Figure 3 shows a typical threshold modulation curve (after Patel 1966). It shows the minimum threshold modulation required by the eye to distinguish between objects at different contrast levels, under optimum viewing conditions, 50 percent of the time. The curve neglects image motion, exposure time, wavelength and vibration effects and other degradation factors and so must be considered a best case curve. The Patel curve was generated when viewing a display at a 25 inch viewing distance with a 100 ft-L average brightness (which is typical of aircraft display daylight operation). The minimum modulation required is about 4 percent, at very low spatial frequencies. The minimum modulation required increases as the spatial frequency increases until a point is reached where no amount of modulation is discernible.

Just discernible gray shade steps were calculated for the monochromatic and polychromatic displays, with the black levels equal to the veiling glare values and each successively brighter step brighter by 1.04, 1.06, 1.08 or 1.10 of the preceding step. The first few steps of the monochromatic display, at the $TM = 0.04$ level are, 50, 52, 54.08, 56.24 etc. The maximum display brightness of the monochromatic display was assumed to be 283 ft-L plus 50 ft-L of veiling glare, or 333 ft-L. These values are typical of early F-16 displays and will vary somewhat between display types. The maximum display brightness of the polychromatic display was assumed to be 250 ft-L plus 93 ft-L of veiling glare, or 343 ft-L. This value was the best case number for an F-18 display, supplied by the manufacturer.

Figure 8 shows the maximum number of gray shades that a pilot could discern, when viewing monochromatic (50 ft-L veiling glare) and polychromatic (93 ft-L veiling glare) displays in 10K ft-L daylight conditions, for threshold modulation values between adjacent shades of .04, .06, .08 and .10. Note that the performance of the polychromatic display is significantly lower than that of the monochromatic display, due to the lower brightness and the larger veiling glare component.

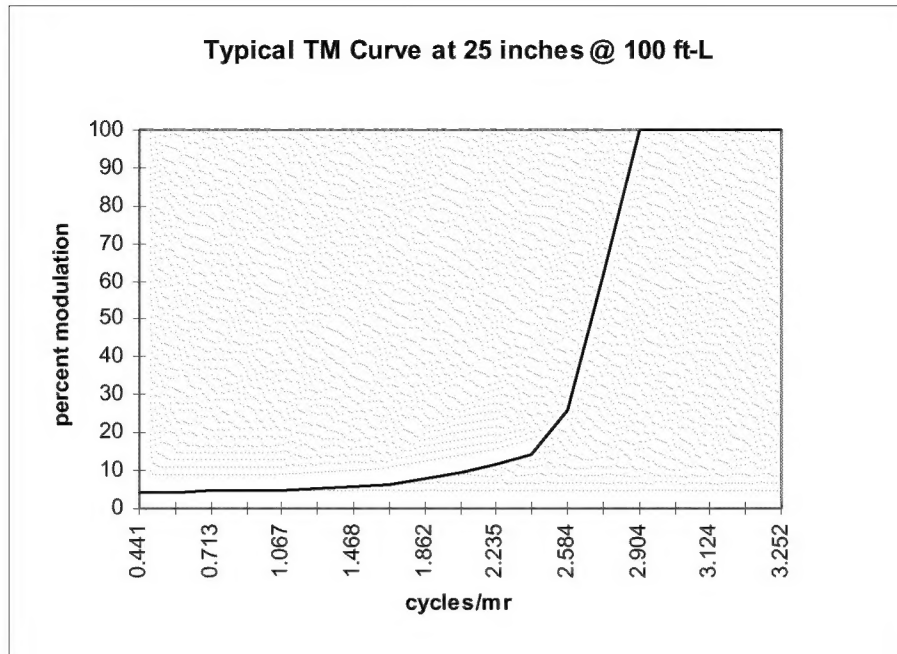


Figure 7. Typical Threshold Modulation curve representative of daylight viewing conditions

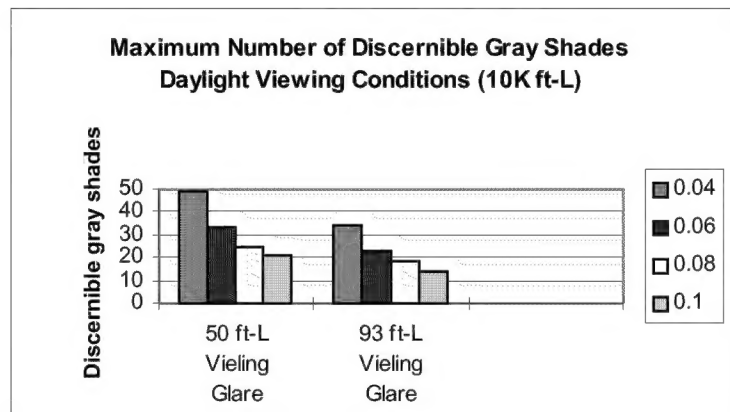


Figure 8. The maximum number of gray shades that a pilot can discern when viewing monochromatic and polychromatic displays under 10K ft-L daylight viewing conditions (for contrast modulation values of 0.04, 0.06, 0.08 and 0.10)

Figures 9 and 10 are plots of the minimum discernible temperature difference, using the monochromatic and polychromatic displays at 10K ft-L, with a range of apparent scene temperatures, at the aperture, ranging between 2 and 20 degrees K. For illustration purposes, the curves for each threshold modulation level were calculated by dividing the temperature range by the number of discernible shades. In actuality, the minimum discernible temperature difference would be a non-linear function of temperature within the scene as well, with a less temperature difference required in toward the black and more temperature required toward the white ends of the video (assuming white is hot).

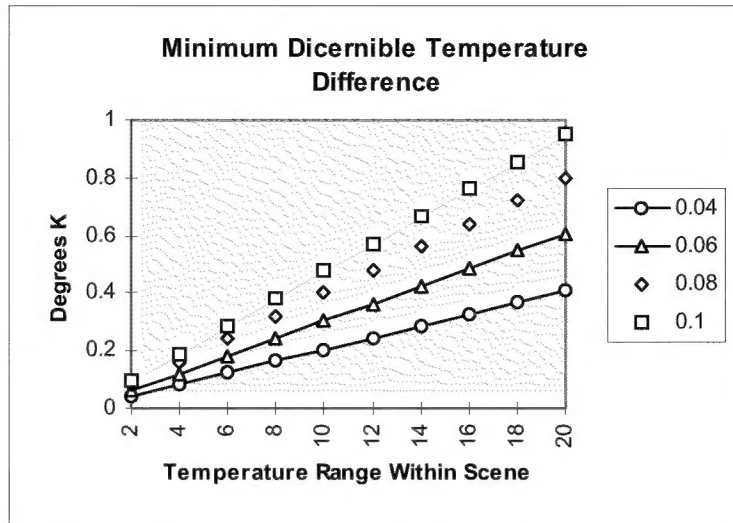


Figure 9. The minimum discernible temperature difference achievable as a function of the apparent scene temperature range at the sensor aperture for a monochromatic display (for contrast modulation values of 0.04, 0.06, 0.08 and 0.10)

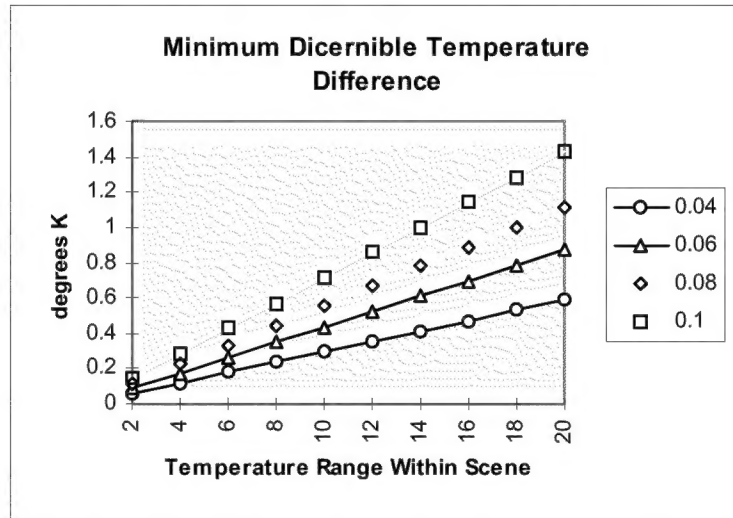


Figure 10. The minimum discernible temperature difference achievable as a function of the scene temperature range at the sensor aperture for a polychromatic display (for contrast modulation values of 0.04, 0.06, 0.08 and 0.10)

The temperature difference required by the user will exceed the NEDT of the sensor, for either display when the temperature range within the image exceeds only a few degrees. The system will be limited by contrast when this occurs and thermal sensitivity will become secondary.

As an example, assume the following scenario:

- ❑ An IR system consists of a FLIR and a polychromatic display
- ❑ The IR sensor has a predicted 2D MRTD value of 0.05 degrees K at 5 cycles/mr.
- ❑ The apparent instantaneous dynamic range of the image is 10 degrees K
- ❑ The ambient brightness on the display is 10K Ft-L
- ❑ The required contrast modulation is .06 at the spatial frequency of interest

From the figures:

- ❑ The maximum number of discernible temperature differences, for a polychromatic display, with
- ❑ .06 contrast steps, in 10 K Ft-L viewing conditions is about 23
- ❑ The average minimum discernible temperature difference would be 0.43 degrees K, which is almost an order of magnitude greater than the 2D MRTD prediction

MODULATION TRANSFER FUNCTION

Modulation transfer functions were calculated for a polychromatic Kaiser F-18 MDI display (typically used to display the FLIR video). Manufacturer's test data was used to calculate typical horizontal and vertical MTFs, with and without veiling glare on the display. The equation used for MTF is:

$$MTF = (B_{\max} - B_{\min}) / (B_{\max} + B_{\min} + 2 * B_{\text{glare}})$$

It should be noted that this definition of the MTF equation is not classical, in that the MTF at 0 lp/in is not unity. The effects of this MTF can be modeled in FLIR92, as a discrete transfer function. Figures 11 and 12 show measured MTF from one point near the center of F-18 MDI display (s/n 811). Only a few data points were measured by the vendor, so the curves are coarse. Figure 13 is a plot of FLIR92 2D MRT data for a display with and without veiling glare. There is a strong negative effect on MRT at all spatial frequencies.

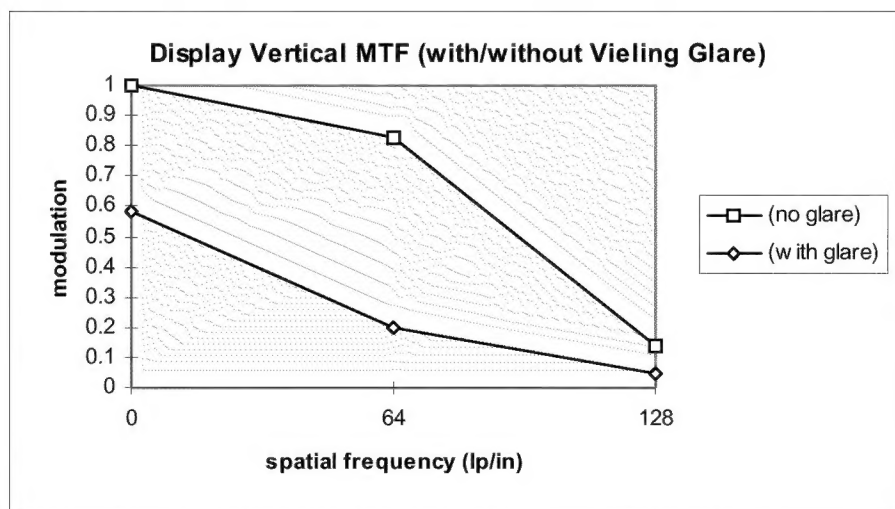


Figure 11. The vertical modulation transfer function of a polychromatic F-18 MDI display, with and without an incident veiling glare

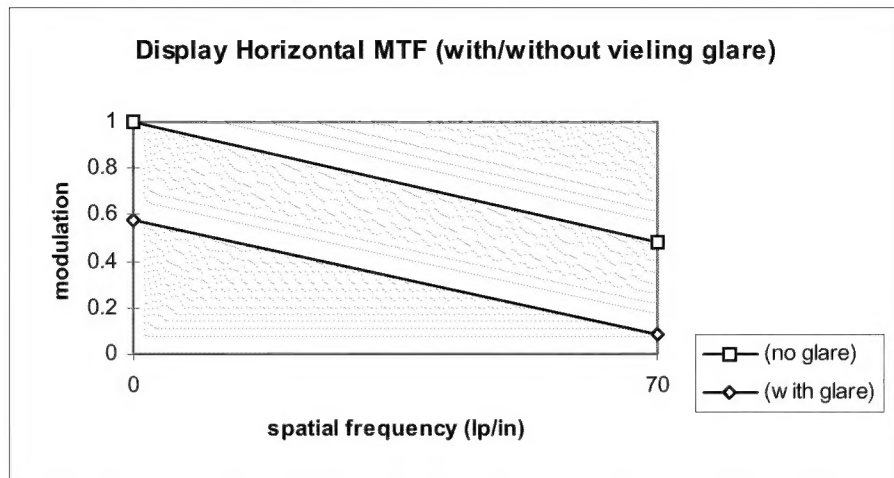


Figure 12. The horizontal modulation transfer function of a polychromatic F-18 MDI display, with and without an incident veiling glare

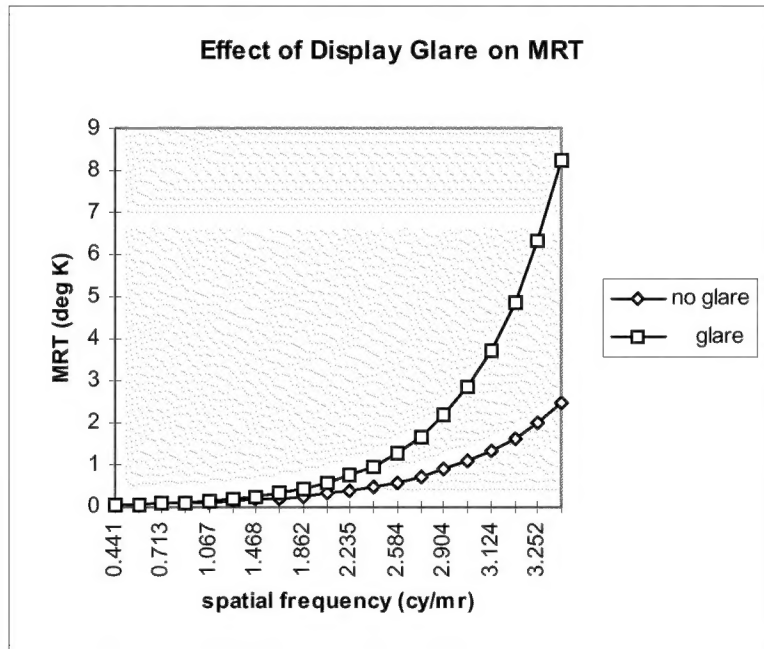


Figure 13. 2D MRT curves from FLIR92 runs, with and without veiling glare present on the display

Figures 14 and 15 contain the FLIR92 2D MRT plots, as shown in figure 13, combined with Minimum Discernible Temperature Difference plots (MDTD) based on TM curves, for 5 and 10 degrees of instantaneous dynamic range. Note that the MRT plots are superseded at all frequencies, with only a 5 degree apparent temperature range in the scene. The system is display/eye limited under these lighting and dynamic range conditions. It is estimated that the system will begin to be display/eye limited at brightness levels well below these brightness levels.

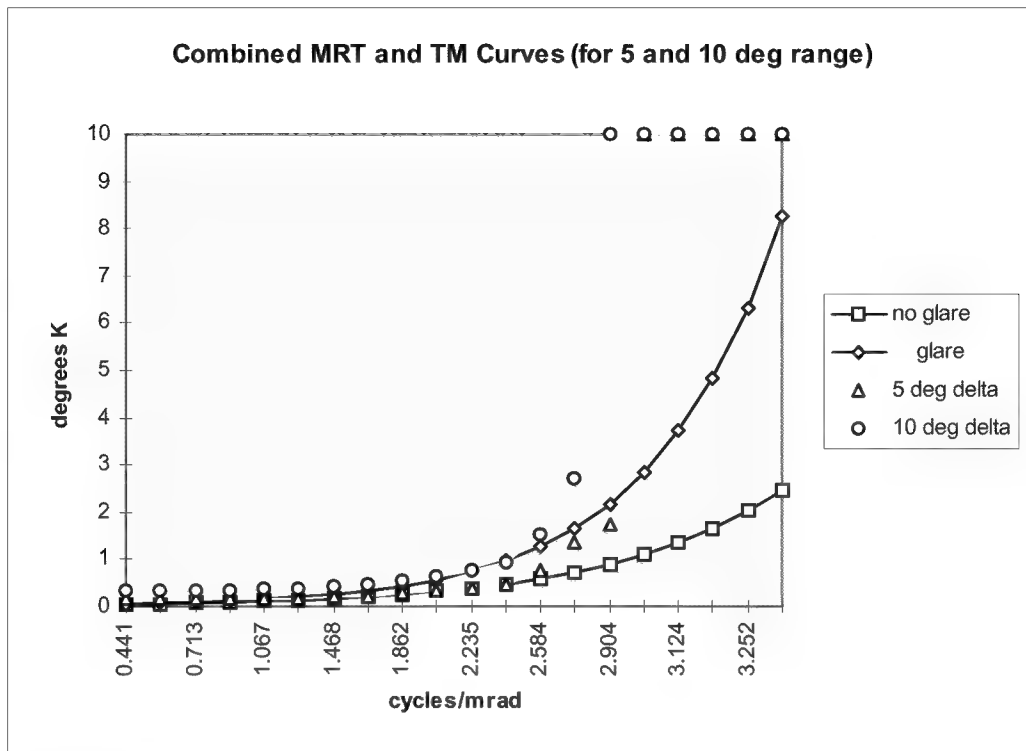


Figure 14. FLIR92 based MRT plots combined with TM based plots for 5 and 10 degree K instantaneous dynamic range on display

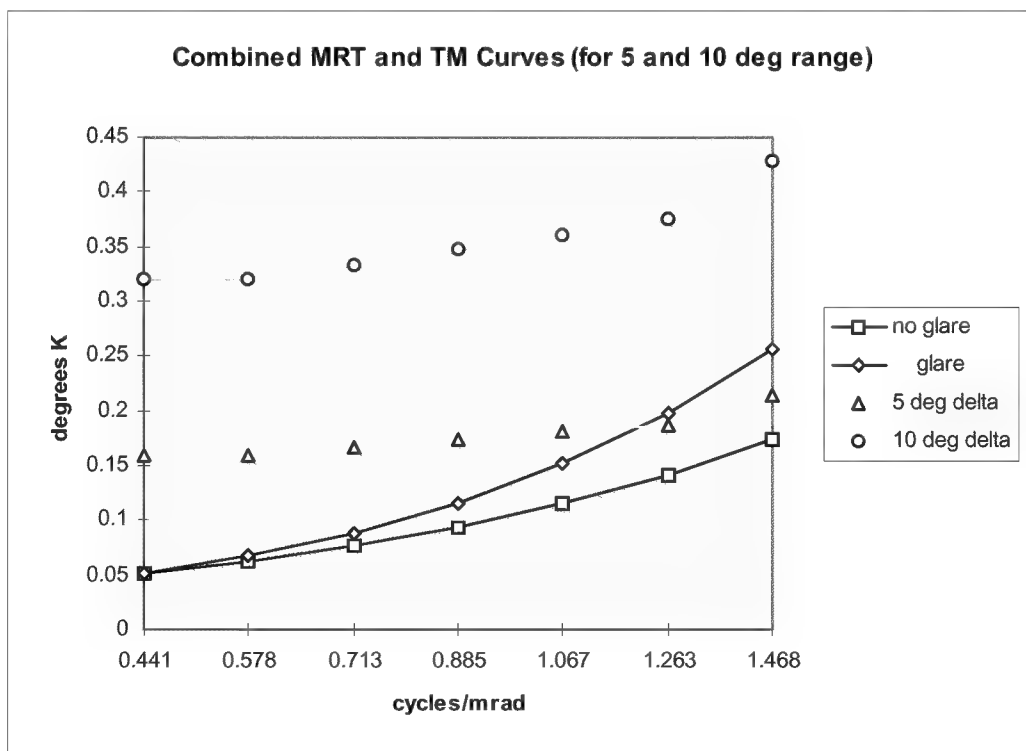


Figure 15. An higher resolution plot of the low spatial frequency data shown in figure 14

RESPONSE TIME

The FLIR92 model does not consider response time. If the system is intended to engage any targets in which complete a priori information is not available, regarding target location, orientation, etc. then serious consideration must be given to the amount of time available to accomplish the acquisition and higher order tasks expected of the MITL. Biberman considered the feasibility of acquiring a 20' x 8' x 8' vehicle (with no a priori information) at two miles, in an uncluttered field, under ideal viewing conditions. He assumed a 4 inch display viewed at 20 inches (which the author assumes roughly equivalent to the F-18 5" display viewed at about 25 inches). Using acquisition time studies by Steedman and Baker and Ludvigh and Miller, Biberman came to these conclusions:

“if the electro-optics is good, an observer can find the vehicle on a smaller screen - it just will take longer, maybe much longer, depending on the display size, brightness, contrast, clutter, etc. One can be sure however that any attempt to display the vehicle image on a 4-in. display tube will be rewarded by a combined record of failure or of very slow operator response compared to that obtained with a 17-in. display tube, which the calculations show is the necessary minimum.”

“it becomes quite clear that , regardless of the contrast - and these data are all for high-contrast situations- the amount of time that is going to be required to find small targets on the face of a conventional 4-in. display is so prohibitive it would be impractical to try and show them”

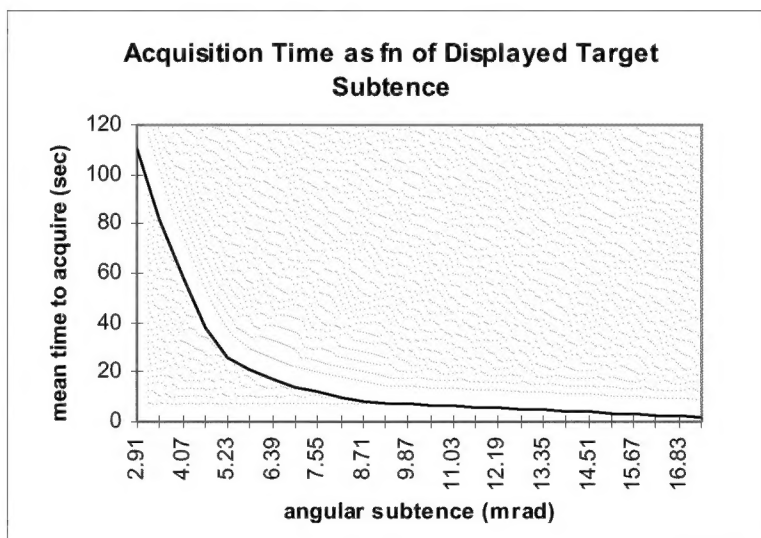


Figure 16. An average of the Ludvigh and Miller acquisition data with angular subtense converted to mrad

Figure 17 was computed using Biberman's rationale and the data used in figure 16. The angular subtense of a large and a small target were calculated as a function of range to target. At each range, the estimated times to acquire were calculated. Those times were plotted with the remaining time to the target. In both cases, the targets required more time than was available, just to acquire. It seems reasonable that additional time would be necessary to accomplish higher order tasks (recognition, identification, designation, etc.).

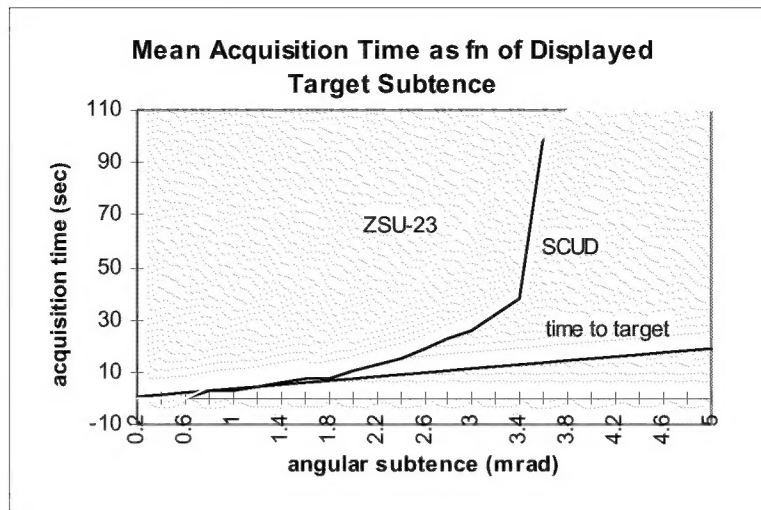


Figure 17. Estimated times required to acquire 2 military vehicles as a function of displayed angular subtense

If complete information is available to the pilot regarding target location, etc. then it is expected that acquisition time will become significantly less important.

THRESHOLD SIGNAL-TO-NOISE RATIO

According to Rosell and Wilson, the threshold signal-to-noise ratio SNR_{TH} in FLIR92 or the display signal-to-noise ratio SNR_{DI} as defined by Rosell, is the SNR required in a given video bandwidth required to permit various visual tasks to be conducted from displayed imagery with various levels of confidence. The FLIR92 default and recommended value is 2.5, *for optimal viewing condition*.

$$MRT = \frac{SNR_{TH}}{(t_E)^{0.5}} * [\text{everything else}]$$

Recognition requires a higher signal-to-noise ratio than detection and recognition in clutter requires a higher SNR than is required in an uncluttered scene. The range of SNR_{DI} values Rosell and Wilson measured which were required to recognize military vehicles at confidence levels of 50 and 95 percent, is shown in Table 1.

Table 1

Typical SNR_{DI} Values for Military Vehicles

| | 50% probability | 95% probability |
|------------|-----------------|-----------------|
| no clutter | 3.3 | 6.6 |
| in clutter | 3.8-5.0 | 7.6-10 |

The range of SNR_{DI} values Rosell and Wilson measured which were required to detect, recognize, and identify various images in uniform and cluttered fields, is shown in Table 2. The 95% probability estimates for Tables 1 and 2 were determined using their Probability vs. Normalized SNR_{DI} curve.

| Table 2 | | | |
|---|------------|-----------------|-----------------|
| Typical SNR_{DI} Values for Military Vehicles | | | |
| | | 50% probability | 95% probability |
| Detection | no clutter | 2.8 | 5.6 |
| Detection | in clutter | 2.5 - 4.8 | 5.0 - 9.6 |
| Recognition | no clutter | 2.5 - 4.8 | 5.0 - 9.6 |
| Recognition | in clutter | 3.4 - 6.4 | 6.8 - 12.8 |
| Identification | no clutter | 3.0 - 5.8 | 6.0 - 11.6 |
| Identification | in clutter | no data | no data |

The data in the tables indicates that the default value of SNR_{DI} may be low. Since the airborne FLIRs are typically expected to provide a MITL with the ability to perform higher order tasks, the proper value might be up to 3 times greater than the current value of 2.5. It important to note that Rosell cautioned potential users of their data, that the SNR_{DI} values presented in *Perception of Displayed Information* were measured under optimum viewing conditions and not in a real world environment. They do not include glare, time factors, stress, raster effects or any other degrading external effects. Rosell did state that glare can be included as a modulation modifier and raster effects could degrade the imagery noticeably, especially in situations where the users have high visual acuity i.e., pilots. The SNR_{DI} also assumes that the display brightness and gain are unlimited, and that the user's visual acuity is not limited by the display. All of the degradation factors listed will increase the threshold SNR_{DI} values listed in the two tables, required to do any task.

Johnston's Criteria for the resolution required for various discrimination levels assumes that the system signal-to-noise ratio and image contrast are sufficient. The signal-to-noise ratio is inversely related to the system resolution and greater resolution is required to achieve higher levels of object discrimination. The larger the target, the smaller the SNR required to detect it. Patterns resolved at the threshold SNR_{DI} are just discerned at a 50% confidence level. Since SNR_{DI} is a significant driver in the MRT equations, any error in selecting the appropriate value for SNR_{DI} will significantly impact the MRT estimate and subsequent performance predictions.

CONCLUSIONS AND RECOMMENDATIONS

The cockpit displays used in tactical aircraft, will be a major limiting factor in determining the ability of a man-in-the-loop trying to perform higher order visual tasks, during daylight operations. Contrast reducing veiling glare from direct and in-direct sunlight, incident on the display, will limit performance to a level significantly below the performance predicted by models based on the standard performance metrics applicable to imaging infrared sensors. Even when the appropriate input variables are used (to reflect the extremely difficult MITL operational environment), the current FLIR models do not adequately consider contrast effects and will predict significantly higher performance than what will be achievable in practice. Future FLIR performance models should take the display limitations into account.

It is highly unlikely that higher order visual tasks can be accomplished in a tactical aircraft environment, with any degree of effectiveness during daylight, without additional aids to the MITL. Pre-processing of in-coming video is mandatory to at least partially off-set the display contrast and size limitations, time line limitations, etc. Automatic target search, queuing and recognition algorithms, intelligent gamma correction, selective magnification, and local area processing all have the potential of significantly increasing the effectiveness of daylight MITL operations. Future FLIR performance models should incorporate pre-processing techniques as they become available.

In any case, because monochromatic displays are significantly better than polychromatic displays, at least one monochromatic display should be available in the cockpit if daylight performance is required.

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